Behaviour of Fixed and Free Head Piles in a Laterally Sliding Soil

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SUMMARY The response of a pile in unstable soil, undergoing sliding lateral movement from the surface to a known depth, is analysed using a numerical soil-structure interaction method capable of incorporating non-linear pile-soil interface behaviour.

The effect of head fixity and depth of slide are investigated for a simplified soil profile. Both the linear and full collapse response are modelled and the pile response is presented in terms of generated maximum bending moment and pile shear force at the level of the sliding soil base. The possibility of large pile rotations causing axial stretching of the pile, and the achievement of the yield moment of the pile, result in practical bounds to the applicability of the results.

The solutions presented for maximum bending moment can be used for the design of piles in areas of instability, and the solutions of shear force at the slide depth for the assessment of the potential improvement of slope stability due to the presence of piles.

1. INTRODUCTION

Typical practical situations in which lateral soil movements can become important include bridge pier foundations, off-shore platform piles and rows of piles in soil stabilisation works. The first two situations are examples where piles support a structure and the integrity of the piles, usually related to maximum bending moment, is important; whereas, for the stabilisation piles it is the horizontal resistance provided by the pile as a shear force at the depth of the slide that is required. For many situations the heads of piles in foundations are assumed fixed within a massive pile cap, which restricts pile head rotations. It is possible that the assumption of no rotation is not valid in practice, owing to the large pile head fixing moments that are required. In this paper, the two extreme cases of a fully fixed pile head and a completely free pile head are considered for the case of uniform lateral movement of a layer of soil. The response is investigated in terms of the generated maximum bending moment and shear force at the slide depth, and particular attention is given to the amount of slide movement associated with the attainment of ultimate strength of the pile-soil system.

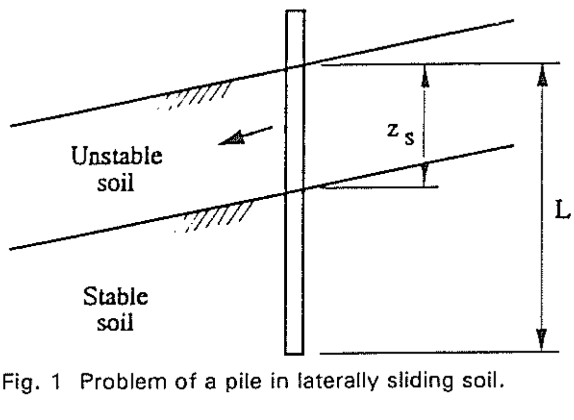

Fig. 1 Problem of a pile in laterally sliding soil.

2. MECHANISMS OF BEHAVIOUR

The problem of a pile penetrating an unstable sliding soil layer and founding within a stable soil region below, is illustrated in Figure 1. Assuming the unstable soil continues to slide and generates a limiting "pressure" p_u (i.e. $p_u d$ is the distributed loading, where d is the pile diameter) at positions along the pile, three possible modes of failure for the pile-soil system arise in which the soil fails. A fourth mode is also possible when the limited strength of the pile precludes full mobilisation of the soil strength, because a section (or sections) of the pile reach the pile yield moment. Figure 2 gives examples of the three basic modes of soil failure and one mode of pile failure, as follows:

i) Short pile failure of the soil occurs along the pile length in the stable soil when it is much shorter than the slide depth, and the pile moves with the sliding soil ("short pile" mode).

ii) Flow of soil around the pile in the sliding layer is possible for some slide depths which are much shorter than the pile length, and the pile remains effectively stationary ("flow" mode).

iii) Intermediate depths to those of the Flow and Short mode require the soil to fail along the pile in both the sliding and stable region, and have large pile rotations ("intermediate" mode).

iv) "Long" pile modes are associated with an incomplete formation of any of the three modes of soil failure, when the yield moment of the pile is reached (here the "short" mode is shown). The standard use of the term "long pile" mode assumes the full plastic moment of the pile has been attained and also that the soil has reached a limiting state of lateral bearing capacity. For the purpose of this paper the "long pile" mode is the result of terminating the analysis when the bending moment at any section first attains the yield moment.

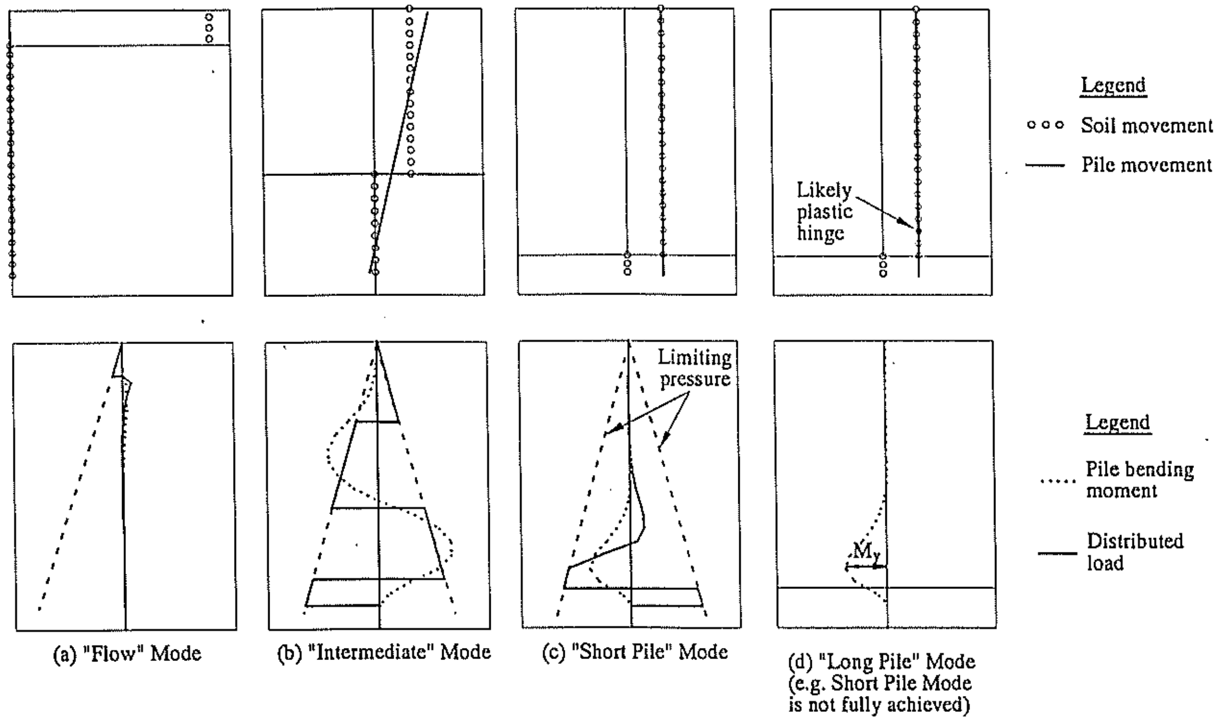

Fig. 2 Examples of distributions of deflection, bending moment and distributed load generated by sliding soil.

3. METHOD OF ANALYSIS

A modified boundary element analysis (Hull et al 1991) was employed to solve for the pile response to lateral soil movements. The analysis can model both pile head and tip loading, with a wide range of boundary conditions. An elastic continuum or spring-based model of the soil, with non-uniform properties with depth, can be specified, Hull (1987). A non-linear response is provided by an interface element that can model both strain hardening and softening responses prior to attaining the ultimate state. The source of the horizontal soil movements, as well as the generation of the shear stresses at the interface between the sliding and stable soil, are not considered beyond the effect of the soil displacing laterally. For example, the vertical movements that may accompany lateral soil displacements are not included.

4. RESULTS OF PARAMETRIC STUDY

In order to be specific, values of parameters required in the analysis were selected to be representative of realistic pile and soil conditions. The values of pile bending stiffness adopted typify reinforced concrete piles of circular section with diameters of 0.5, 1.0 and 1.5 m, or steel tube piles with the same diameters and respective thicknesses of 8, 16 and 24 mm. The pile length was held constant at 40 m. The Young's modulus of the stable soil E_s was taken as either 20 or 50 MPa, consistent with undrained soil shear strength c_u of 40 or 100 kPa for $E_s/c_u = 500$ (e.g. Davies and Budhu, 1986). The sliding soil was assigned a Young's modulus value of half that of the stable soil, to make some allowance for the increase of soil stiffness with depth which commonly occurs in natural deposits. Similarly, the limiting pile-soil "pressure" p_u in the sliding soil was given a value of half that in the stable soil (e.g. Viggiani, 1981), where $p_u = 10c_u$ was used such that $E_s/p_u = 50$.

For the three pile diameters and two values of soil stiffness analyses were carried out for different slide depths. Fixed and free head conditions were modelled.

4.1 Effect of Slide Movements

Curves for different values of slide depth, showing the development of the maximum bending moment and the bending moment at the slide depth as the slide movement increases, are presented in Figure 3. Both the fixed and free head cases for the largest diameter pile and stiffest soil are presented. For the fixed head case the head fixing moment is also shown, while for the free head case the pile rotation at the slide depth is presented.

It is clear that the pile-soil system attains a limiting state at which the generated bending moments do not change for further slide movements. This is a result of the soil lateral bearing capacity being exhausted. Unlike the bending moments, the pile rotation at the slide depth for the free head case continues to increase with slide movement, for slide depths between 36% and 85% of the pile length. This is consistent with the Intermediate mode of failure of a free head pile, where pile rotation is predicted without considering the axial stresses caused by the pile lengthening.

The free head pile reaches the soil limiting state at smaller slide movements than the fixed head pile and smaller moments are generally produced. Even so, the largest calculated maximum moments are much greater than a typical value of pile yield moment of the order of 10 MNm. Obviously, the "long" pile mode will often be observed before the limiting state of the soil occurs.

Similar statements apply for soil with a Young's modulus of 20 MPa except that a higher relative pile-soil stiffness reduces the soil movements needed to develop p_u.

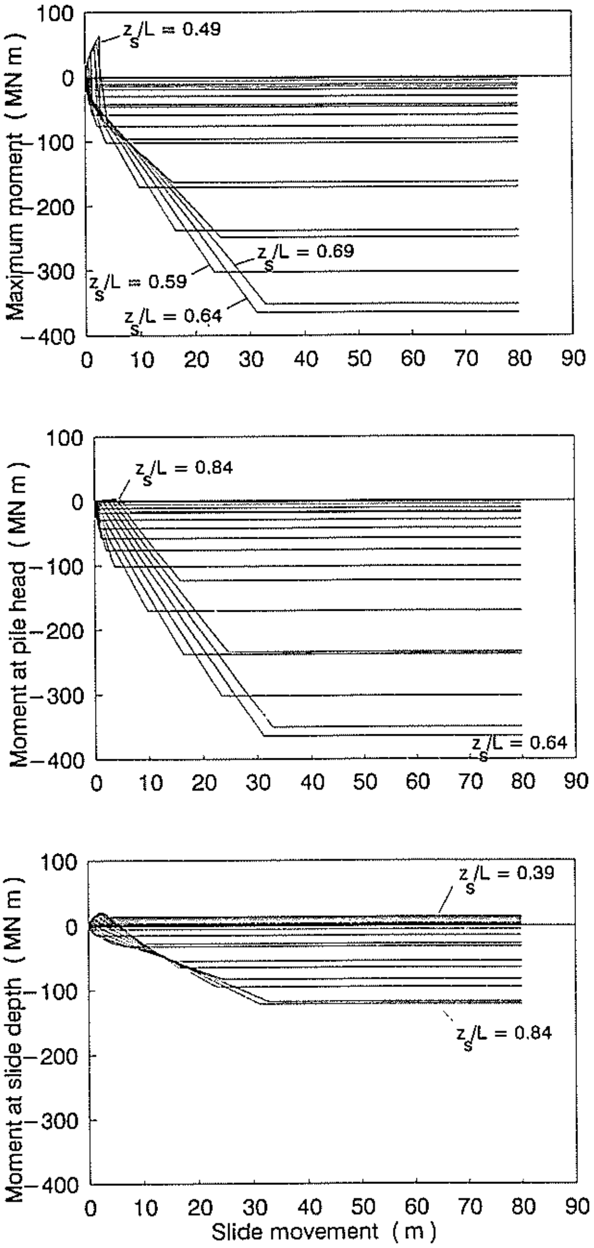

Fig. 3a Bending moment maximum, moment at head and moment at slide depth for fixed–head pile.

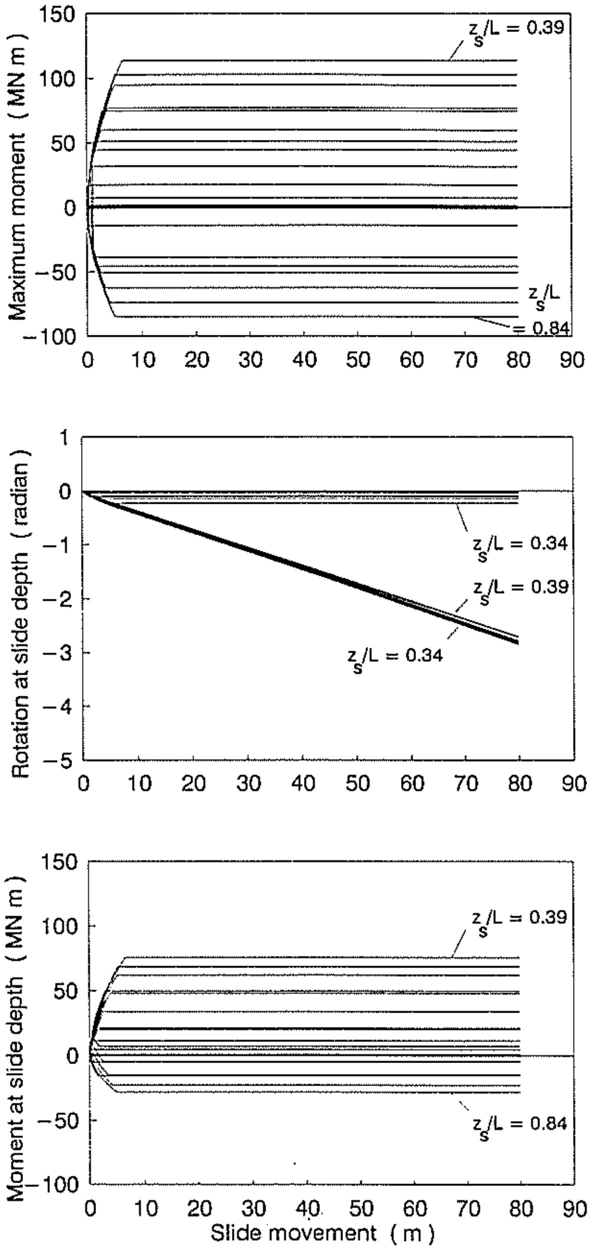

Fig. 3b Bending moment maximum and, rotation and moment at slide depth for free–head pile.

4.2 Deflected Pile Shapes

Figure 4a and 4b clearly shows the three modes of failure where the pile displaced shapes, after an extremely large soil movement of 40 m, are plotted for the stiffer soil.

For slide depths of up to 85% of the pile length the head fixity has some influence on the deflected shape, but for deeper slides the head fixity has no effect. This depth of slide corresponds to the first occurrence of the Short mode of failure (for the free head pile and without allowance for failure of the pile), in which the sliding soil carries the pile through the stable soil.

The deflected shapes of the fixed head pile for the slide depths of 13.5 and 19.5 m (and generally less than 67% of the pile length) illustrate the "flow" mode of soil failure. Whereas, the free head pile only generates the "flow" mode for the shallower depths (less than 36% of the pile length). This is consistent with an enlargement of the extent of the "flow" mode and also the extended range of the "short pile" mode to eliminate the "intermediate" mode when the pile head is fixed.

Unrealistic lengthening of the pile would be required to produce the Intermediate failure mode of the free head pile, and also the fixed head pile failure for slide depths between 50% and 75% of the pile length. However, for the small deformation assumptions of the analysis, the states achieved from the analysis are theoretically correct.

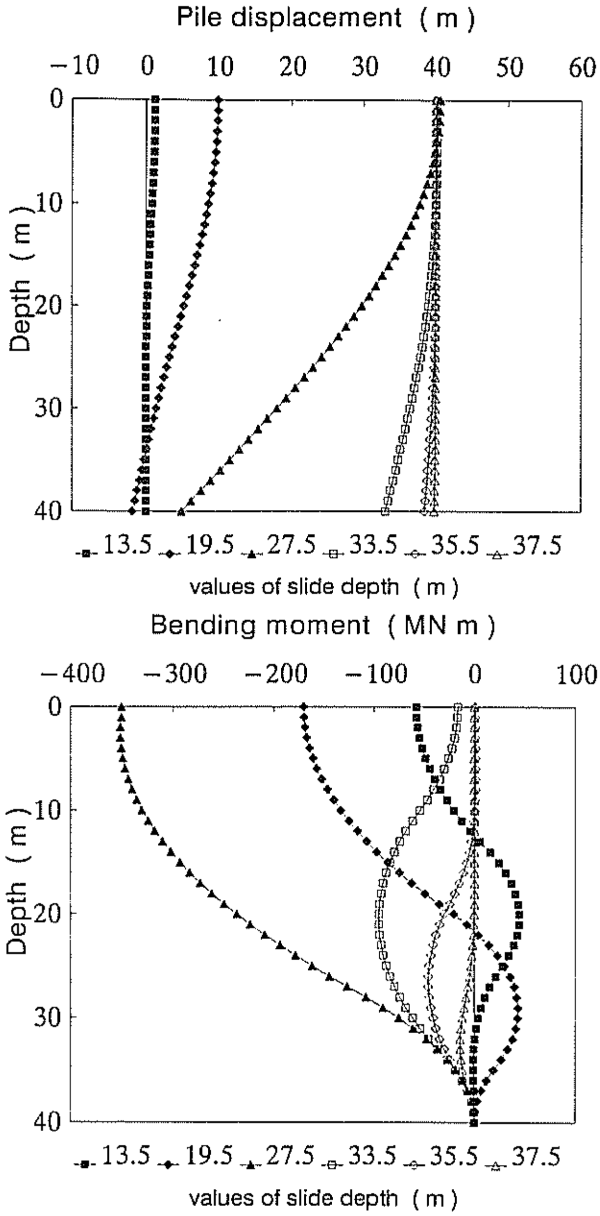

Fig.4a Fixed head pile response with Young's modulus of 50 Mpa and 1500 mm diameter pile.

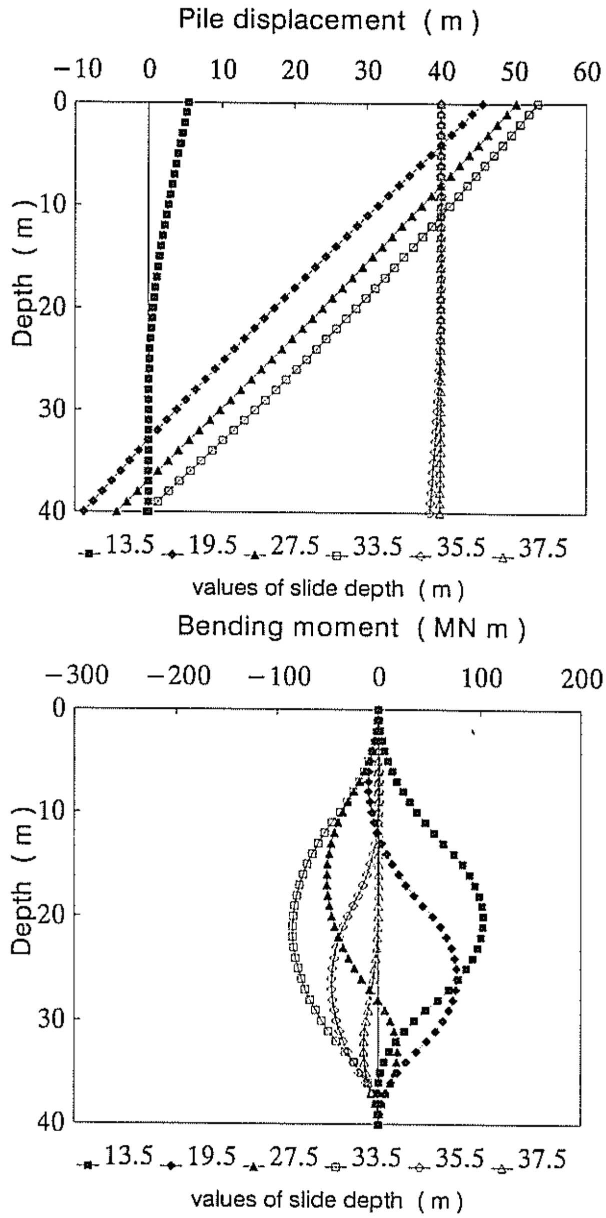

Fig.4b Free head pile response with Young's modulus of 50 Mpa and 1500 mm diameter pile.

4.3 Pile Bending Moments

For both cases of head fixity, the maximum moment must change sign when the location of the maximum moves from one position to another, as indicated by the near vertical lines near the origin of the upper graphs in Figure 3. Large negative bending moments occur at the head for the fixed head pile when the slide depth is less than 70% of the pile length. The free head pile develops much smaller negative bending moments but larger positive bending moments than the fixed head pile.

As seen in Figure 3, the bending moments at the slide depth are predominantly negative for the fixed head pile and positive for the free head pile, although the range of absolute magnitudes are similar.

Figure 4 also displays the distribution of bending moments for selected slide depths. The two curves depicting the deeper slide depths are identical for the fixed and free head piles, as expected for "short pile" modes of soil failure. The "flow" mode does not have a corresponding similarity between fixed and free head responses, because the head fixing moment actually reduces the maximum moment. However, it must be remembered that large head fixing moments may be impossible to achieve in practice.

4.4 Shear Force at Slide Depth

The shear force at the level of the slide, needed for stability calculations, is presented in Figure 5 versus the dimensionless slide depth z_s/L. The stiffer soil, three pile diameters and both head fixity conditions are considered.

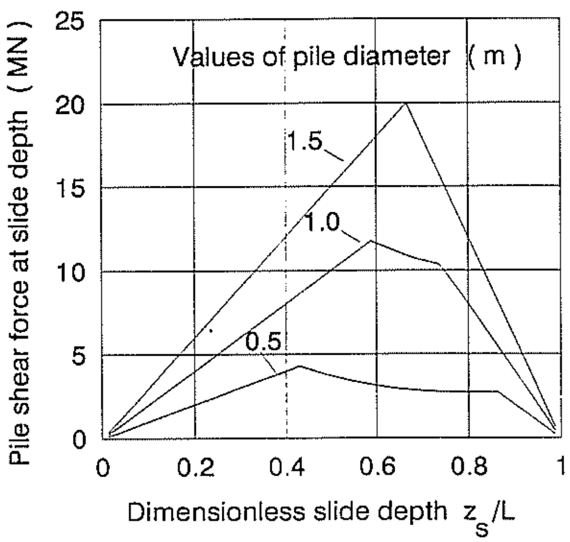

Fig. 5a Shear force developed in the pile at the depth of the slide for the fixed head pile in the stiffer soil.

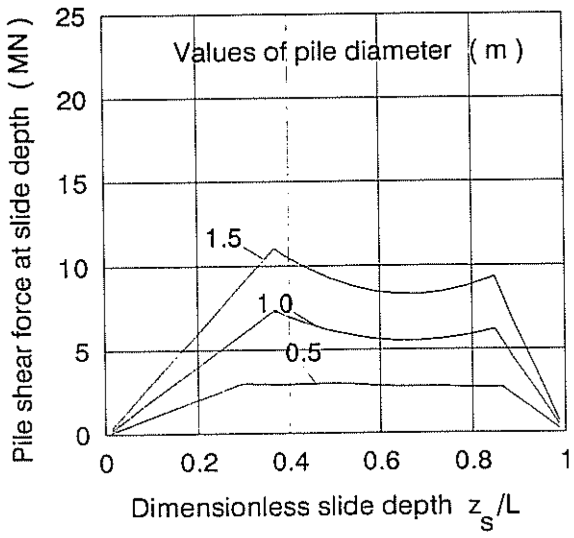

Fig. 5b Shear force developed in the pile at the depth of the slide for the free head pile in the stiffer soil.

It is clearly shown that the shear force developed during the "flow" and "short pile" modes are linearly dependent upon the slide depth and also proportional to the pile diameter. The 1.5 m diameter pile has developed complete failure of the soil (as can be seen in Figure 3) for both fixed and free head piles. Thus, the fixed head pile has a failure locus that consists of two straight lines, joining at a value of z_s of two thirds the pile length. This is a result of choosing the magnitude of p_u in the sliding soil to be half that in the stable soil.

For pile diameters 0.5 and 1.0 m the fixed head pile did not generate full soil failure at the extremely large soil movement of 80 m, and the triangular shape of the failure curves is truncated by a curved line. In Figure 5b, the free head pile failure curves are truncated by the "intermediate" mode of failure for diameters of 1.0 and 1.5 m. However, the 0.5 m diameter pile curve is truncated by both a curve for "intermediate" failure and two curves for incomplete generation of full soil failure between slide depths of 30% and 50% and between 75% and 86% of the pile length.

4.5 Limited Pile Strength

No pile will have unlimited strength to resist bending; a commonly used method to account for this is to limit the allowable extreme fibre axial stress in the pile. As a first approximation for the maximum axial stress in the pile, the rotation at the slide depth (which is generally the maximum rotation) and the bending moment at the slide depth, M_s may be used. The axial strain component corresponding to rotation of the pile, without vertical displacement of the pile, may be expressed in terms of the rotation θ as

$$\epsilon_{axial} = \frac{(1 - \cos\theta)}{\cos\theta} \qquad (1)$$

and, together with the extreme fibre stress caused by bending, the maximum stress can be written,

$$\sigma_{max} = E_p \left(\epsilon_{axial} + \frac{M_s d}{2E_p I_p} \right) \qquad (2)$$

which may be calculated for each stage of the analysis.

For a set of values of σ_{max}/E_p a plot of dimensionless shear force at the slide depth versus dimensionless slide depth is shown in Figure 6 for the 1.5 m diameter pile in the stiffest soil. Both fixed and free head boundary conditions are considered. The head fixity is seen to be relatively unimportant for the smallest presented value of dimensionless maximum axial stress, σ_{max}/E_p = 0.001, with only slide depths between 10% and 40% of the pile length predicting any benefit from fixing the pile head. This possible benefit relies upon the head fixing moment being sustainable by both the pile and the means by which the head is fixed. Figure 4a shows that a fixing moment of some 60 MNm is required at collapse when the slide depth is 34% of the pile length. But the value corresponding to the σ_{max}/E_p = 0.001 curve is 11 MNm.

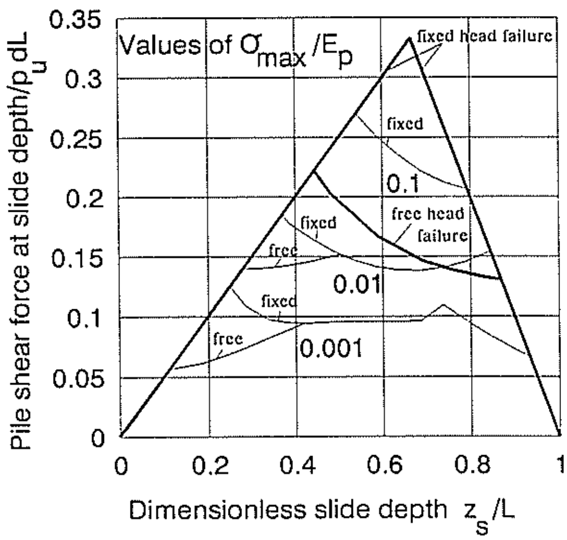

Fig. 6 Shear force developed in the pile at the depth of the slide for values of maximum fibre pile stress.

This is still greater than the pile yield moment of 10 MNm and permanent damage would occur to the pile.

5. CONCLUSIONS

The entire pile response to the "short pile" mode of failure is found to have no influence from the fixing of the pile head, because the mechanism of failure for this mode is already essentially that of a pile with head fixed in the sliding soil.

For differing head fixity the "flow" mode does not produce different values of shear at the slide depth, because the failure mechanism only involves horizontal pile-soil "pressures" (these are assumed not to change with head fixity). The head fixing moment only enlarges the range of slide depths within which "flow" type failure occurs. The response similarity does not extend to other measures of response, e.g. the deflected pile shapes and bending moment distributions are greatly influenced by head fixity.

"Intermediate" modes of soil failure, since they involve axial stretching of the pile, may not fully develop. The pile strength and/or axial pull-out strength of the pile in the soil may be insufficient to accomodate the large rotation required before this mode is produced. Previous solutions to this problem, such as Viggiani (1980), have recognised the importance of the component of maximum axial stress in the pile accompanying bending, but the techniques that were employed have no way of assessing the rotations and deflections necessary to mobilise soil and pile strengths.

The results indicate that large head fixing moments are generated, and large pile rotations are required to achieve full collapse (with a non-yielding pile). The results from the analyses therefore cast doubt upon the validity of using a small displacement formulation for the solution of such problems, without due attention to axial response. A method of considering the axial stress is presented and leads to the conclusion that the range of slide depths within which fixing the pile head is advantageous is rather limited.

6. ACKNOWLEDGEMENTS

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